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SEARCHING FOR NEW MATTER PARTICLES AT FUTURE COLLIDERS*

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ABSTRACT

We discuss the production of new particles that are predicted by many extensions of the Standard Model, at future high–energy pp, eP and e^+e^- linear colliders. We focus on the case of exotic, excited and di–fermions.

1. Introduction

Many theories beyond the Standard Model (SM) of the electroweak and strong interactions, such as Grand Unified Theories, Composite Models or Technicolor, predict the existence of new matter particles. These particles can be cast into three categories: exotic fermions, excited fermions and difermions. In this talk, I will discuss the prospects for producing some of these new particles at future pp [LHC with $\sqrt{s} = 14$ TeV], eP [LEP×LHC with $\sqrt{s} = 1.2$ TeV] and e^+e^- linear colliders [NLC with $\sqrt{s} = 0.5$–1 TeV with its $e^+e^-, \gamma\gamma$ and $e\gamma$ modes]. The present write–up summarizes a study which has been performed in a recent report [1], to which we refer for a more detailed discussion and for a complete set of references.

2. Exotic Fermions

These fermions are exotic with respect to their transformation under the SM group: they have the usual lepton and baryon quantum numbers but non–canonical $\mathrm{SU}(2)_L\times \mathrm{U}(1)_Y$ quantum numbers, e.g. the left–handed components are in weak isosinglets and/or the right–handed components in weak isodoublets. These particles are predicted by Grand Unified Models which have a single representation into which a complete generation of SM quarks and leptons can be naturally embedded. In most cases, these representations are large enough to accommodate new fermions which, in fact, are needed to have anomaly–free theories. For instance, in the group E_6 which is suggested as a low energy limit of some superstrings theories, each fermion generation lies in the **27** representation and, in addition to the 15 SM chiral fields, 12 new fields are needed to complete the representation.

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The classic examples of new fermions include: sequential 4th generation fermions [with the neutrino having a right-handed component for its mass to be generated in a gauge invariant way]–such fermions are not truly 'exotic' in the usual sense; vector fermions with both left- and right-handed components in weak isodoublets [in E_6 there are two–isodoublets of heavy leptons for each generation, and an isosinglet vector colored particle], mirror fermions which have the opposite chiral properties as the SM fermions and isosinglet fermions [which are more frequently discussed in the literature] such as the SO(10) Majorana neutrino.

It is conceivable that these fermions, if for instance they are protected by some symmetry, acquire masses not much larger than the Fermi scale. This is even necessary for purposes of anomaly cancellation if the new gauge bosons which are generic predictions of Grand Unified Theories are relatively light. In the case of sequential and mirror fermions [at least in the simplest models where the SSB pattern is the same as in the SM], unitarity arguments suggest that the masses should not exceed a few hundred GeV. These particles, if they exist, could be therefore accessible at the next generation of colliders.

Except for singlet neutrinos, the new fermions couple to the photon and/or to the electroweak gauge bosons W/Z [and for heavy quarks, to gluons] with full strength; these couplings allow for pair production with practically unambiguous cross sections. If they have non–conventional quantum numbers, the new fermions will mix with their SM partners. This mixing will give rise to new currents which determine the decay properties of the heavy fermions and allow for their single production. If the mixing between different generations [which induces FCNC at tree–level] is neglected, the mixing pattern simplifies. The remaining angles are restricted by LEP and low energy experiment data to be smaller than $\mathcal{O}(0.05 - 0.1)$. Note that LEP1 sets bounds of order $\sim M_Z/2$ on the masses of these particles [stronger mass bounds from Tevatron can be set for quarks]; masses up to M_Z might be probed at LEP2.

The heavy fermions decay through mixing into massive gauge bosons plus their ordinary light partners, $F \to fZ/f'W$. For masses larger than $M_W(M_Z)$ the vector bosons will be on–shell. For small mixing angles, $\zeta < 0.1$, the decay widths are less than 10 MeV (GeV) for $m_F = 0.1(1)$ TeV. The charged current decay mode is always dominant and for $m_F \gg M_Z$, it has a branching fraction of 2/3.

If their masses are smaller than the beam energy, the new fermions can be pair produced in e^+e^- collisions, $e^+e^- \to F\bar{F}$, through s–channel gauge boson exchange. The cross sections are of the order of the point–like QED cross section and therefore, are rather large; Fig. 1a. Because of their clear signatures, the detection of these particles is straightforward in the clean environment of e^+e^- colliders, and masses very close to the kinematical limit can be probed. The total cross sections, angular distributions and the polarization of the final particles allow one to discriminate the different types of fermions. Charged fermions can also be pair–produced at $\gamma\gamma$ colliders, $\gamma\gamma \to F\bar{F}$, and for relatively small masses, the cross sections can be larger than in the e^+e^- mode.

Heavy quarks can be best searched for at hadron colliders where the production processes, $gg/q\bar{q} \to Q\bar{Q}$, give very large cross sections: at LHC with $\sqrt{s} = 14$ TeV and a luminosity of 10 fb^{-1} quark masses up to 1 TeV can be reached using the spectacular $ZZqq \to 4l^{\pm}qq$ signal [with a branching ratio of $\mathcal{O}(10^{-3})$]; see Fig. 2a.

Figure 1: Total cross sections for the (a) pair and (b) single (first generation) production of exotic leptons at the NLC with $\sqrt{s} = 1$ TeV.

Figure 2: Total cross sections for the pair production of heavy quarks at LHC and for the single production of exotic leptons at LEP$\times$LHC.

For not too small mixing angles, one can also have access to the new fermions via single production in association with their light partners. The rate for this type of process is much more model dependent but can substantially increase the reach of a given accelerator. In e^+e^- collisions, this proceeds only via s–channel Z exchange in the case of quarks and second/third generation leptons, leading to small rates. For the first generation leptons, however, one has additional t–channel exchanges which increase the cross sections by several orders of magnitude; see Fig. 1b.

A full simulation of the signals [$e^+e^- \to \nu_e e jj$ for N and $e^+e^- \to e^+e^- jj$ for E] and the backgrounds [mainly from single and pair production of W/Z bosons] has been performed using a model detector, assuming $\sqrt{s} = 500$ GeV and $\int \mathcal{L} = 50$ fb^{-1}. For mixing angles $\zeta = 0.05$ for E and $\zeta = 0.025$ for N, it has been shown that one can reach lepton masses up to $m_L \sim 450$ GeV. For $m_L = 350$ GeV, smaller values of the mixing angles ($\zeta \sim 0.005$ for N and $\zeta \sim 0.03$ for E) can be probed. The angular distributions and the final polarization allow to discriminate between fermions with left- and right-handed mixing, and between neutrinos of Dirac or Majorana type.

Heavy leptons of the first generation can also be singly produced in eP collisions through t–channel exchange; the cross sections are shown in Fig. 2b. At LEP$\times$LHC with $\sqrt{s} = 1.2$ TeV and $\int \mathcal{L} = 2$ fb^{-1}, masses up to 700 GeV for N and 550 GeV for E can be probed, for $\zeta \sim 0.1$. Note that heavy neutrinos of Left–Right models can be produced in eP collisions via t-channel W_R exchange; one finds that at LEP$\times$LHC, the discovery reach in the $m_N - M_{W_R}$ plane is $m_N + 0.38 M_{W_R} < 1090$ GeV. In e^+e^- collisions these neutrinos, when kinematically allowed can be pair produced if the right-handed W bosons are not too heavy [$M_{W_R} < 2$ TeV at $\sqrt{s} = 0.5$ TeV].

3. Excited Fermions

The existence of excited particles is a characteristic signal of substructure in the fermionic sector: if the known fermions are composite, they should be the ground state of a rich spectrum of excited states which decay down to the former states via a magnetic dipole type de-excitation. However, a satisfactory dynamical model is still lacking and a phenomenological input is needed to study this possibility. For simplicity, it is assumed that the excited fermions have spin and isospin 1/2; their

couplings to gauge bosons are vector–like [form factors and new contact interactions may also be present] and that the coupling which describes the transition between excited and ordinary fermions is chiral and inversely proportional to the compositeness scale Λ which is of $\mathcal{O}(1$ TeV).

The excited fermions decay into gauge bosons and their ordinary partners, $f^\star \to fV$. The charged leptons have the electromagnetic decay which has at least a branching ratio of 30%, and the excited quarks decay most of the time into quarks and gluons. These two decays constitute a very characteristic signature and discriminate them from the exotic fermions previously discussed.

If kinematically allowed, excited fermions can be pair-produced without any suppression due to powers of $1/\Lambda$. In e^+e^- and $\gamma\gamma$ collisions, the processes and the cross sections are the same as for vector exotic fermions; the only difference is in the decay modes. Since the latter can be easily searched for, f^* with masses near $\sqrt{s}/2$ can be discovered in these machines. Excited fermions can be singly produced with their light partners and the rates are suppressed by the factor $1/\Lambda^2$. At e^+e^- colliders, for quarks and second/third generation leptons, for which the process is mediated by s–channel boson exchange, the cross sections are very small. But for the first generation excited fermions, one has substantial contributions due to additional t–channel diagrams: W exchange for ν_e^* and Z/γ exchanges for e^*, which increase the cross sections by several orders of magnitude. At a 1 TeV e^+e^- collider, the cross section for e^* is larger than 1 pb across the entire mass range for $\Lambda = 1$ TeV, while for ν_e^* it drops to 100 fb for $m_{\nu^*} \sim 900$ GeV; Fig. 3a. e^* and ν_e^* can be also singly produced in $e\gamma$ collisions [the former as a resonance and the latter in association with a W] with much larger rates, and all excited fermions can be singly produced in $\gamma\gamma$ collisions with appreciable cross sections. For $\Lambda \sim$ few TeV, and if kinematically allowed, excited quarks and leptons can therefore easily be found in such machines.

Due to the special couplings of the electron to the excited leptons of the first generation, one can have single production of e^* through t-channel γ and Z exchange, and ν_e^* through W exchange in eP collisions. For e^* production, one has three different contributions and the cross section is an order of magnitude larger than for ν_e^*. Requiring a few tens of events, masses up to 800 GeV for ν^* and e^* can be probed at LEP$\times$LHC for $\int \mathcal{L} = 2$ fb^{-1}. Background problems make that the detection of the first generation excited quarks is more difficult.

Figure 3: Total production cross sections for single excited leptons at NLC (a) and for single excited quarks (and for the QCD background) at LHC (b).

Excited quarks can be produced in pp collisions through a variety of mechanisms. The dominant production channel is the gluonic excitation of quarks $g+q \to q^*$ which occurs through the q^*qg magnetic interaction; the signature is dijet mass bumps. [Through preon interactions excited quarks and also leptons, could eventually be produced at observable rates.] The cross section are large, and the QCD backgrounds

have been shown to be under control; Fig. 3b. At LHC with $\sqrt{s} = 14$ TeV and a luminosity of 10 fb^{-1}, based on 100 to 1000 events, a mass range of 5–6 TeV can be reached for excited quarks.

3. Difermions

Difermions are scalar or vector particles [spin 1/2 difermions are also discussed in the context of supersymmetric theories] which have unusual baryon and/or lepton quantum numbers. Examples of these particles are leptoquarks (LQ) with B= $\pm 1/3$ and L= ± 1, diquarks with B= $\pm 2/3$ and L= 0 and dileptons with B= 0 and L= ± 2. They are predicted in GUT's [e.g., in E_6, the color triplet weak isosinglet particle in the **27**-plet can be either a LQ or diquark] and in composite models.

In addition to the usual couplings to gauge bosons, difermions have couplings to fermion pairs which determine their decays [here also one can neglect the couplings between different generations to prevent FCNC at tree-level]. These couplings are a priori unknown. In the case of LQ's for example, a systematic description of their quantum numbers and interactions can be made by starting from an effective lagrangian with general SU(3)×SU(2)×U(1) invariant couplings and conserved B and L numbers. This leads to the existence of 5 scalar and 5 vector LQ's with distinct SM transformation properties. In general, present data constrain difermions to have masses larger than 50–150 GeV.

Leptoquarks can be produced in pairs at e^+e^- colliders through gauge boson exchange; significant t-channel quark exchange can be present in some channels if the quark-lepton-LQ couplings are not too small. Depending on the charge, the spin and isospin of the LQ, the cross sections can vary widely. As an example, at $\sqrt{s} = 500$ GeV and assuming $m_{LQ} \sim 200$ GeV, σ varies between 7 fb [for the scalar isosinglet with charge $-1/3$] and 3.3 pb [for the vector iso–triplet]. Through the signatures of 2 leptons plus 2 jets, these states are accessible for masses smaller than the beam energy. The study of the various final states and the angular distributions would allow the determination of the quantum number of the LQ's as in the case of exotic fermions. LQ's can also be pair produced in $\gamma\gamma$ collisions, just as were the exotic fermions; depending on the LQ charge, the cross sections can be much larger or much smaller than for charged leptons.

Single production of scalar and vector leptoquarks can also take place in the e^+e^-, $e\gamma$ and $\gamma\gamma$ modes of the collider. The kinematical reach is thus extended to $\sqrt{s}$ but the production rates are suppressed by the unknown LQ coupling to quark–lepton pairs, $\sqrt{k\alpha}$. The cross sections are shown in Fig. 4. The most important subprocess in this case is $e\gamma \to q$+LQ and the contributions of both direct and resolved photons have to be taken into account. At a 1 TeV e^+e^- collider with $\int \mathcal{L} = 60$ fb^{-1}, one reaches masses close to $\sqrt{s}$ [i.e. 1 TeV for e^+e^-, $\simeq 0.9$ TeV for $e\gamma$ and $\simeq 0.8$ TeV for $\gamma\gamma$). At $e\gamma$ colliders, first generation LQ's are observable for k as small as 10^{-3}.

Since they are strongly interacting particles, LQ's can be produced at hadron colliders with very large rates. At LHC, pair production in the $gg/q\bar{q} \to$ LQ+LQ process leads to cross sections ranging from a few nb for masses around 100 GeV to a few fb for masses $\mathcal{O}(1$ TeV). The rate for vector particles [which depends on

Figure 4: Cross sections for the single production of scalar leptoquarks at $e^+e^-, e\gamma$ and $\gamma\gamma$ colliders: (a) $Q = -5/3$ or $-1/3$ and (b) $Q = -4/3$ or $-2/3$.

Figure 5: (a) Total cross sections for pair production of scalar (dash-dot) and vector LQ's (the dot, dash, dash-dot lines correspond to the qq, gg and total cross sections) at LHC. (b) Total cross sections for single production of vector LQ's at LHC: the dot(dash-dot) is for the $gu(gd)$ subprocess and for $\kappa = 1, 0$.

their anomalous magnetic moment κ] is substantially higher than for scalar particles; Fig. 5a. At LHC with 100 fb^{-1} the search reach for scalar/vector LQ's is 1.4/2.2(1.8) TeV for $\kappa = 1(0)$, if one assumes a branching fraction of unity for the $eejj$ final state.

Single scalar LQ production, through $gu \to e^+$LQ and $gd \to \bar{\nu}$LQ, can also lead to large cross sections for Yukawa couplings $k = \mathcal{O}(1)$; in this case masses up to $\sim$ 1.5 TeV can be reached at the LHC. Vector leptoquarks have larger production rates and the discovery reach can be extended to $\sim$ 2 TeV; Fig. 5b.

Note that eP colliders are ideal machines for the production of the first generation leptoquarks. The latter can be produced as s channel resonances in $e \to$LQ, unless the coupling k is extremely tiny. At LEP$\times$LHC masses up to 1 TeV can be reached, even for k values a few orders of magnitude smaller than unity.

Dilepton production has been considered at e^+e^- colliders in the three modes $e^+e^-, e\gamma$ and $\gamma\gamma$. These particles are accessible up to masses close to $\sqrt{s}/2$ in pair production, $e^+e^-/\gamma\gamma \to X^{++}X^{--}$: the rates [especially in $\gamma\gamma$ collisions because of the charge] are very large and the signatures [four leptons] are spectacular. Dileptons can also be singly produced in the three modes of the collider. In particular, at 1 TeV e^+e^- collider, scalar and vector dileptons can be observed up to masses of $\sim$ 0.9 TeV in the $e\gamma$ mode even for couplings to lepton pairs as small as 10^{-3} the electromagnetic coupling; in the e^+e^- and $\gamma\gamma$ modes, dileptons can be observed for couplings an order of magnitude larger.

Finally, diquarks can be pair produced in e^+e^- and $\gamma\gamma$ collisions for masses smaller than $\sqrt{s}/2$ with appreciable rates, with a signal consisting of an excess of 4 jets events. They can be also pair produced at hadron colliders, either in pairs or singly [for the first generation] if the couplings to quark pairs is not too small. However, since the signals consist only in jets, the large QCD backgrounds might be a problem. In the case of single production, as a dijet resonance, the detection of these particles depends on excellent energy resolution being available.

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References

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